Particle Acceleration in Mildly Relativistic Shocks

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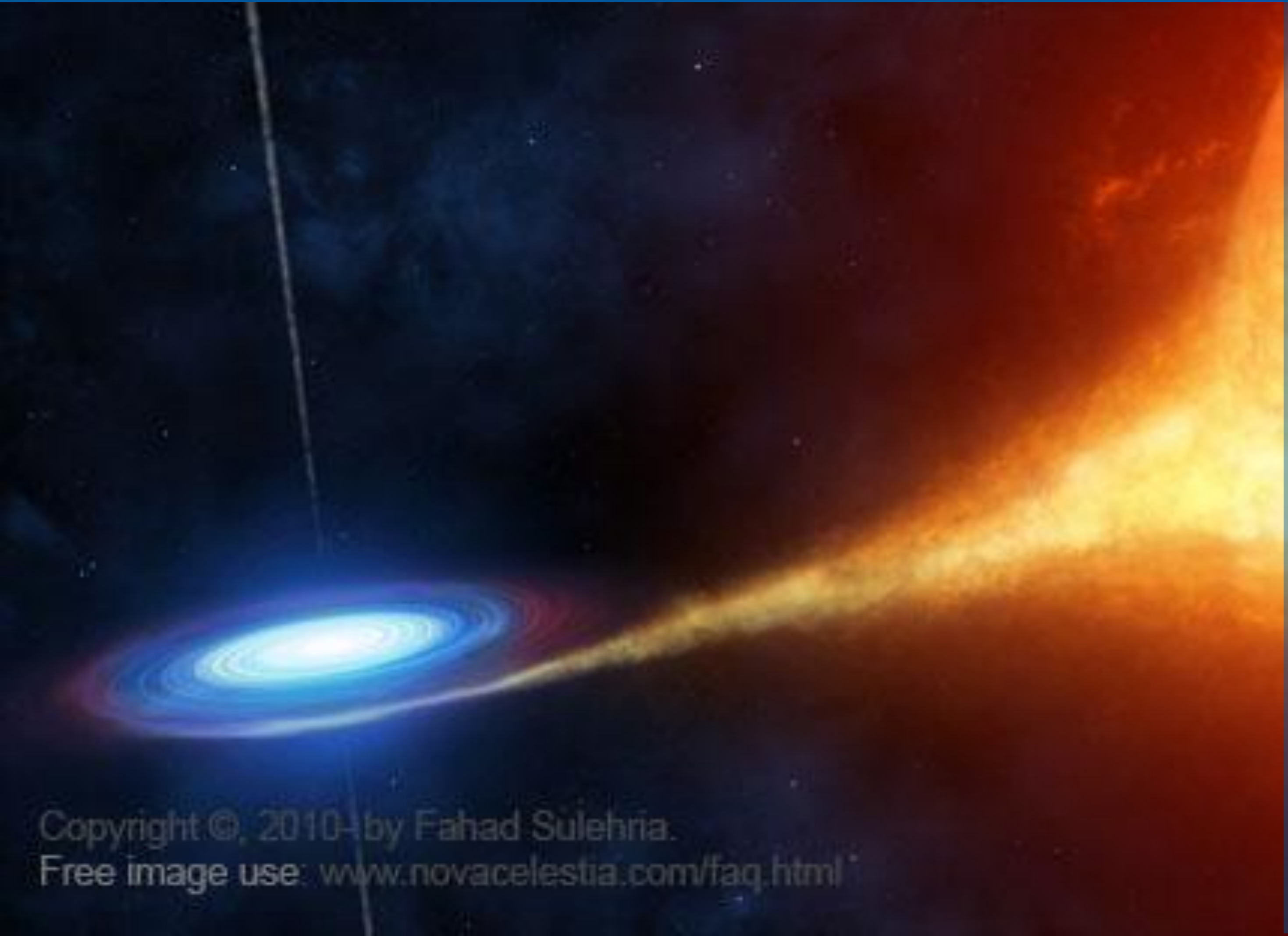
In collaboration with: A. Spitkovsky, D. Caprioli, & S. Markoff

arXiv:1809.10809

PRINCETON UNIVERSITY

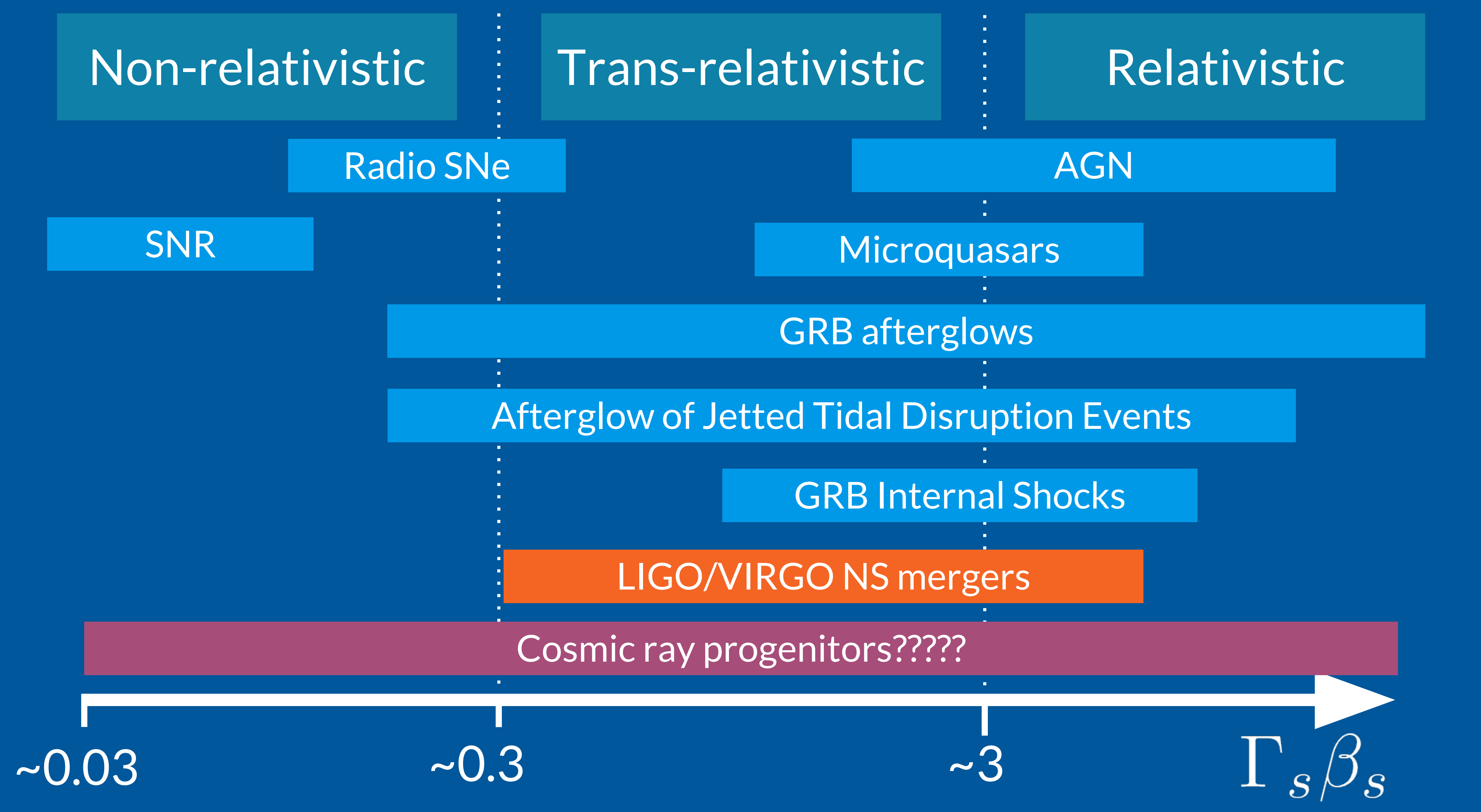
Many luminous astrophysical systems are capable of producing strong shocks.

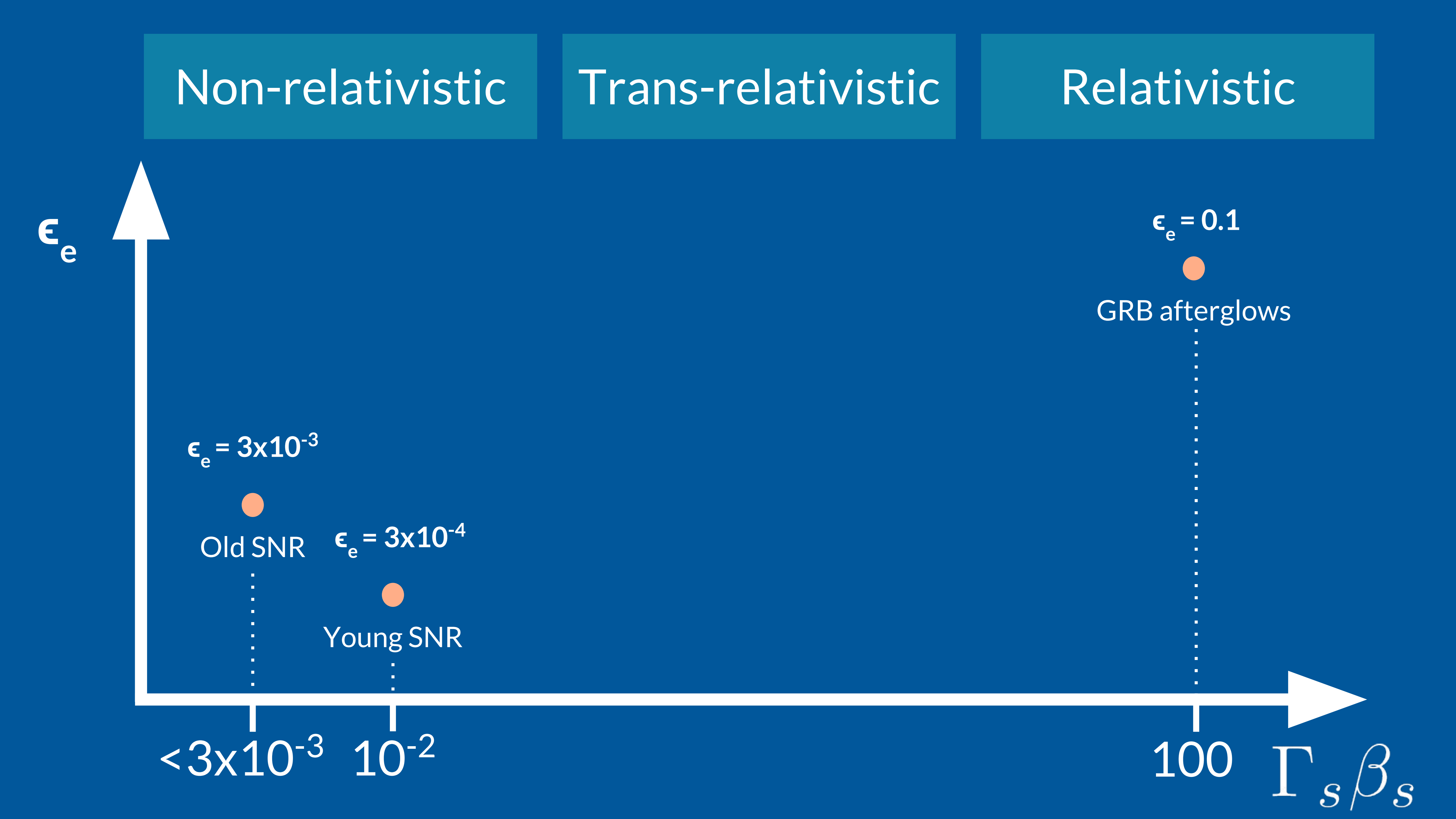


Non-thermal emission is seen in:

- AGNs
- Supernova Remnants
- X-ray binaries
- The outflows of Tidal Disruption Events
- Gamma-Ray Bursts
- Radio-supernovae
- Cosmic rays

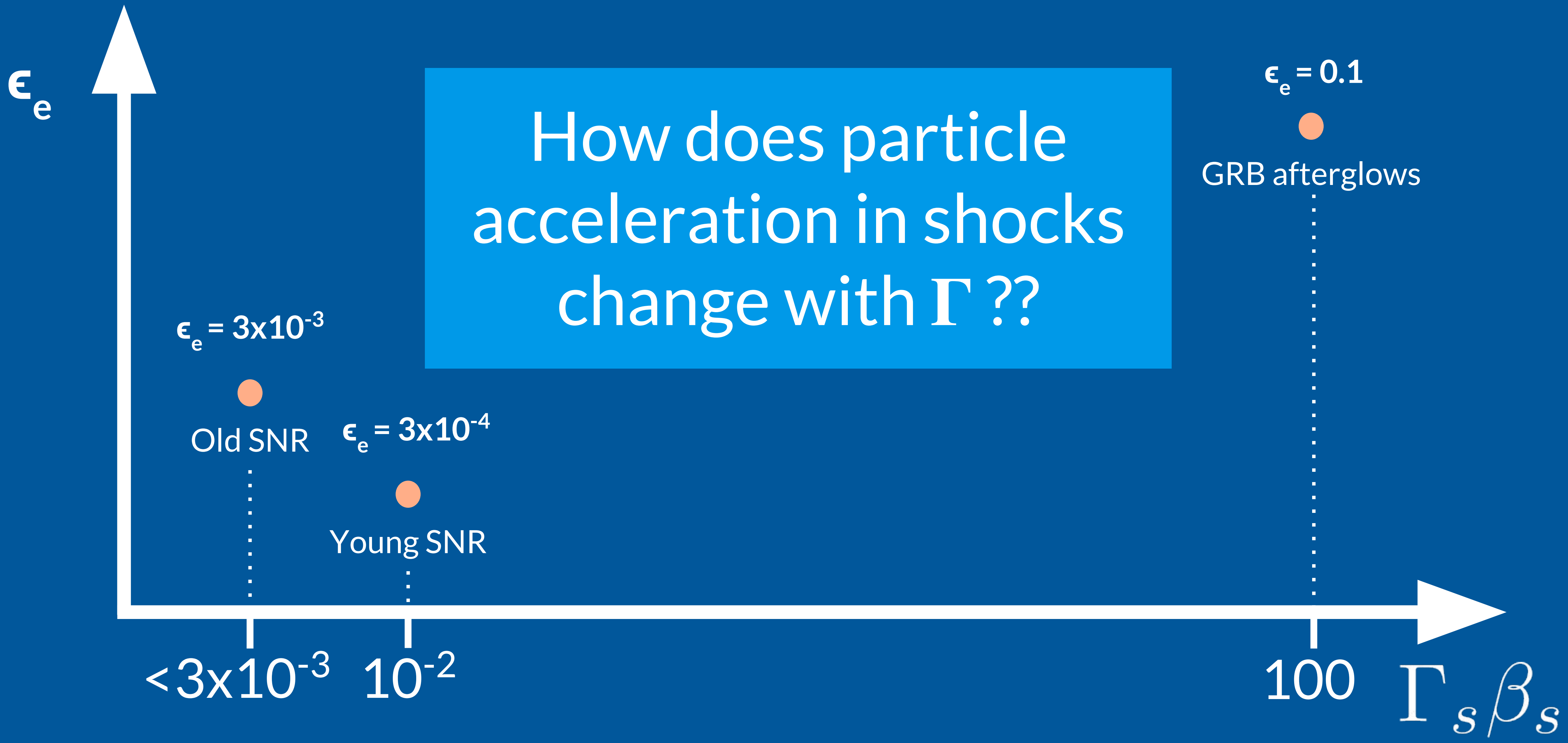
LIGO/VIRGO NS mergers

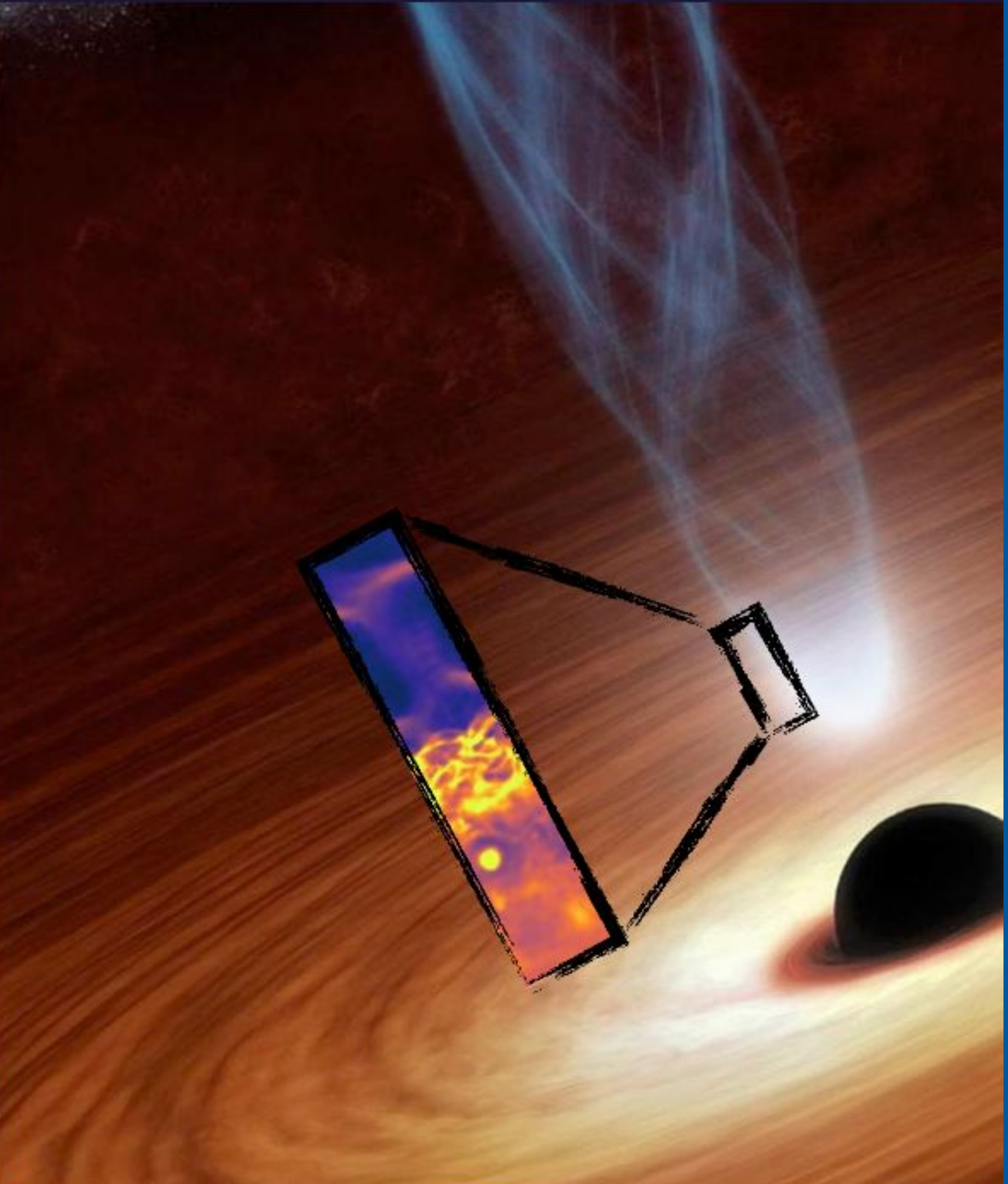

Non-relativistic
Trans-relativistic
Relativistic
Radio SNe
AGN
SNR
Microquasars
GRB afterglows
Afterglow of Jetted Tidal Disruption Events
GRB Internal Shocks
LIGO/VIRGO NS mergers
Cosmic ray progenitors?????
~0.03
~0.3
~3
$\Gamma_s \beta_s$



Non-relativistic
Trans-relativistic
Relativistic
ϵ_e
$\epsilon_e = 0.1$
GRB afterglows
$\epsilon_e = 3x10^{-3}$
Old SNR
$\epsilon_e = 3x10^{-4}$
Young SNR
$<3x10^{-3}$
10^{-2}
100
$\Gamma_s \beta_s$

Non-relativistic | Trans-relativistic | Relativistic





We can also address this question from 'first-principles' by means of self-consistent simulations.

Need to capture the interaction between the fields & the particles self-consistently

Particle-in-cell codes are the ideal tool to study this problem. We used Tristan-MP.

Relativistic quasi-parallel shocks

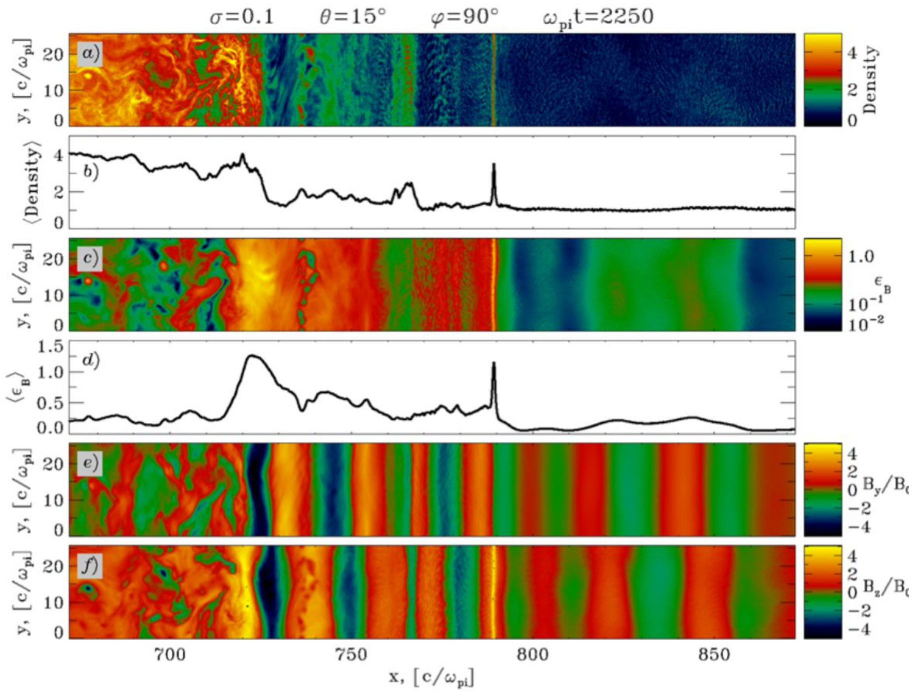
- Efficient energy exchange between electrons and ions in the upstream

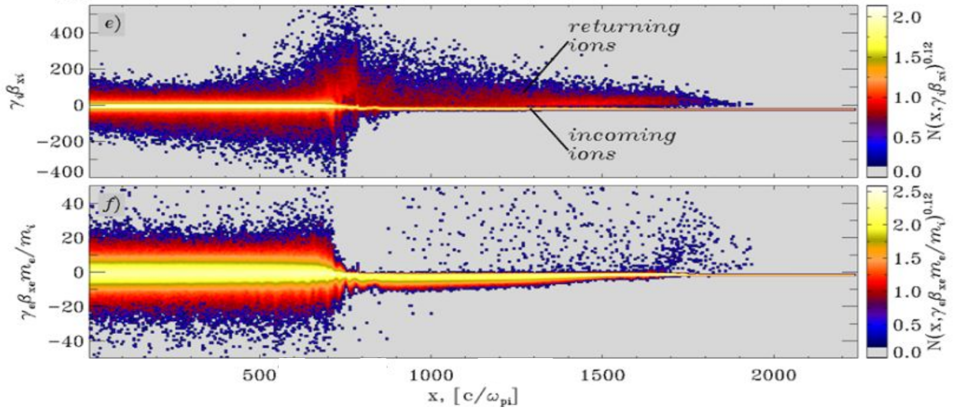
- Preheats electrons to significant fraction of ion energy.

2D PIC

$\epsilon_e \sim 0.1$

Sironi & Spitkovsky 2011

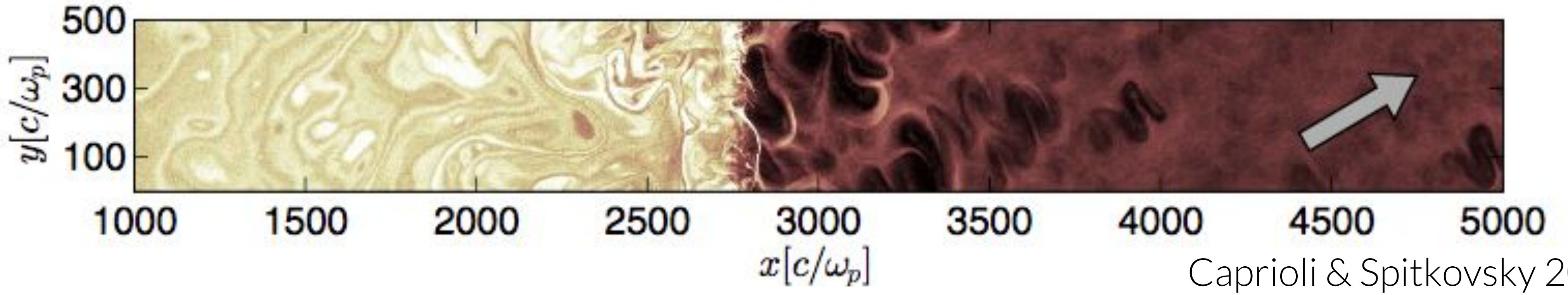




Sironi & Spitkovsky 2011

Non-Relativistic quasi-parallel shocks

Density in a quasi-parallel M=50
Hybrid simulation.



Caprioli & Spitkovsky 2014

- Cosmic rays stream far from the shock, evacuate underdense cavities via a current-driven instability (Reville & Bell 2012; Caprioli & Spitkovsky 2013).

Non-Relativistic quasi-parallel shocks

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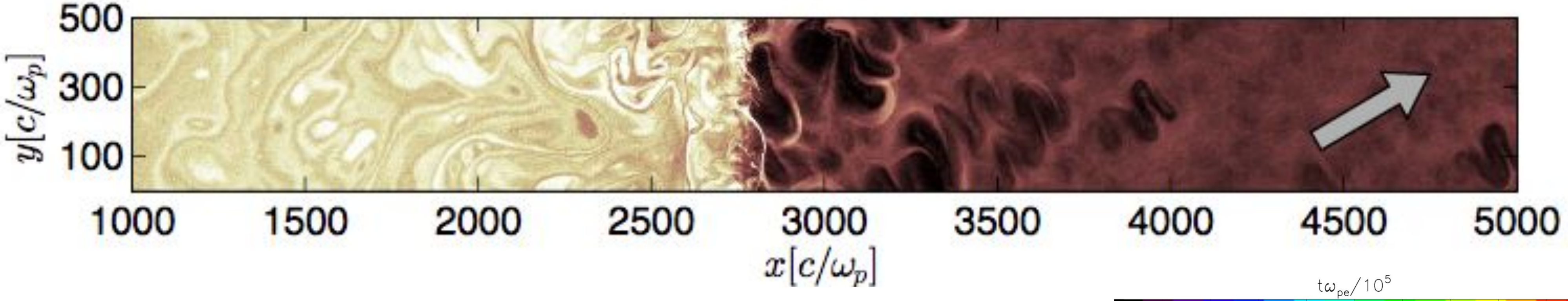
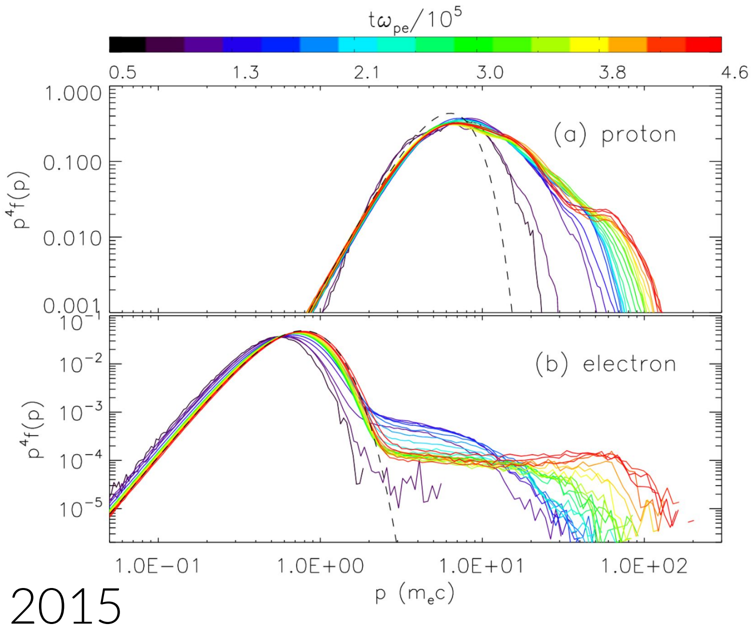
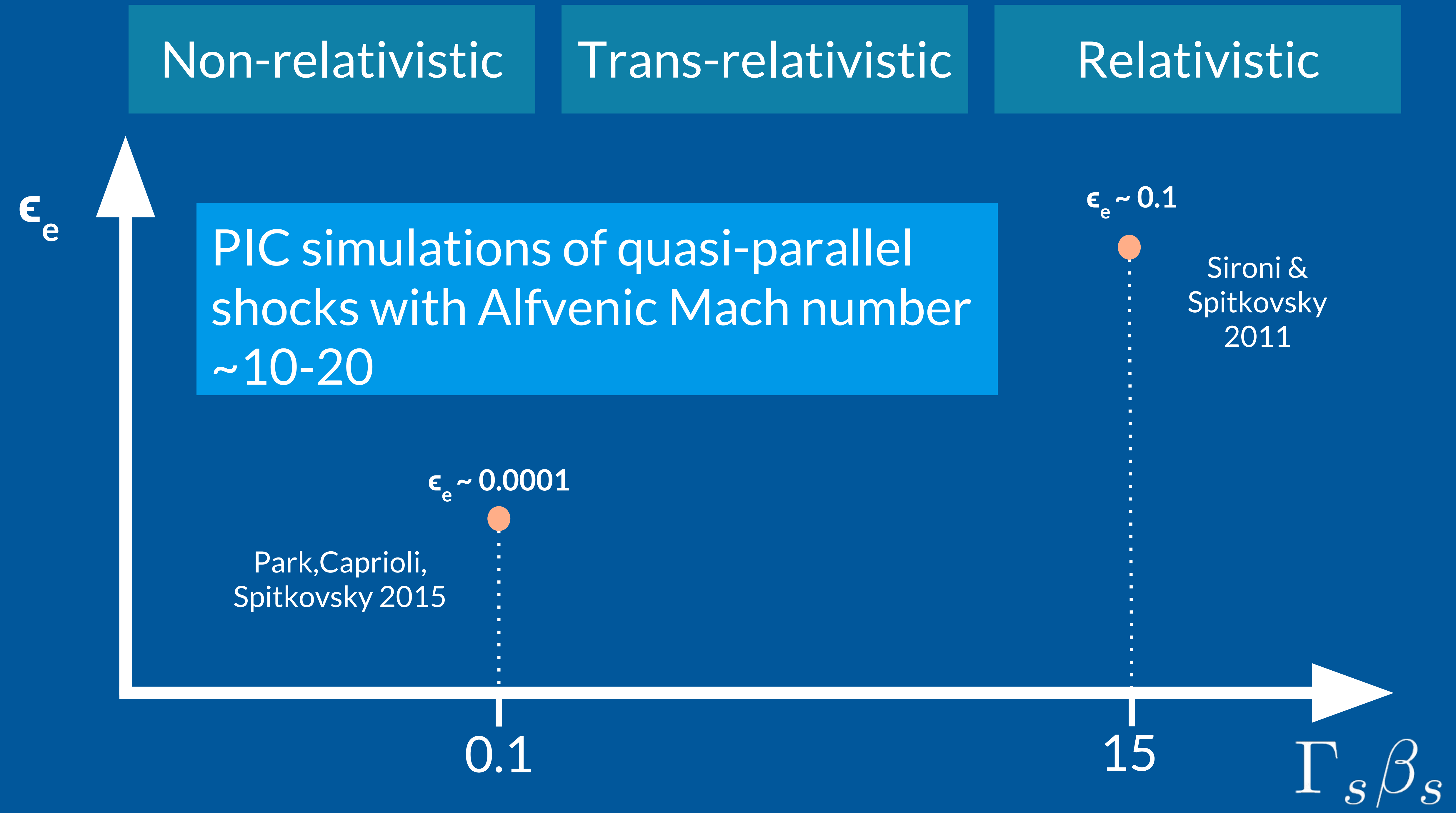
Hybrid simulation.



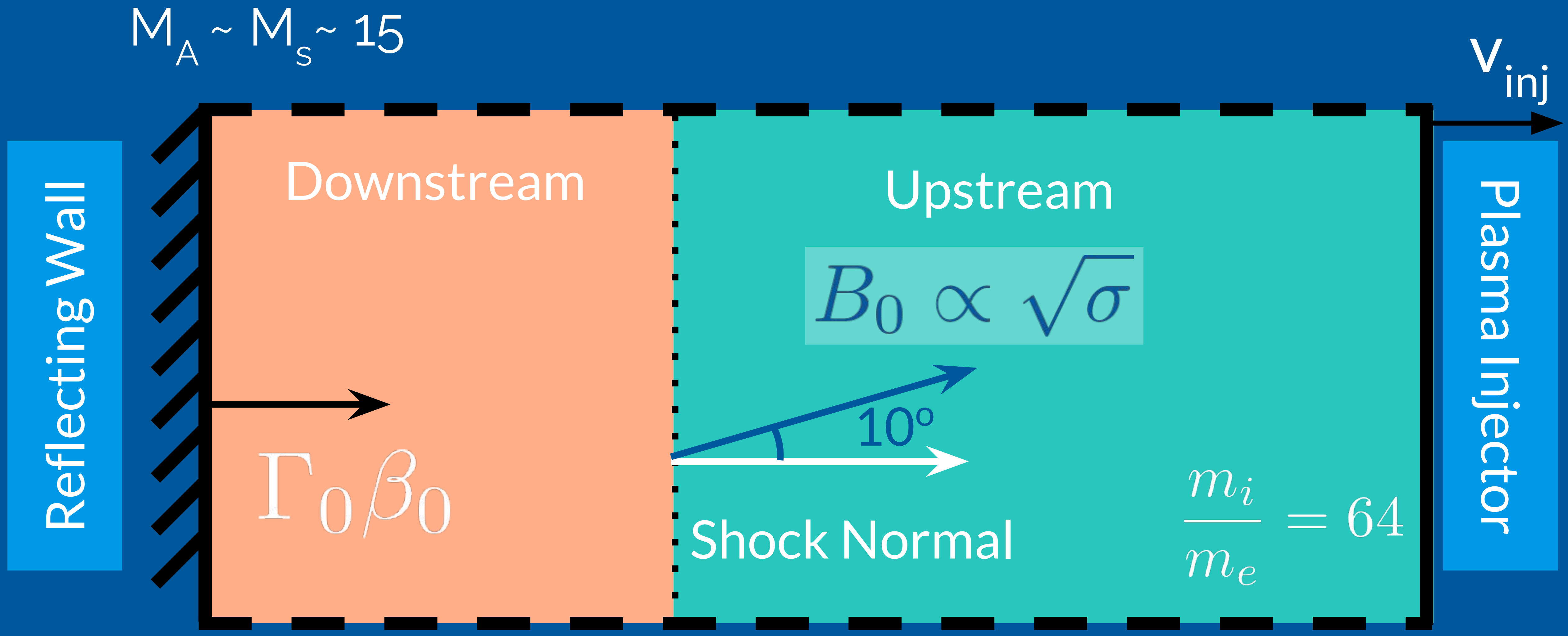
Hybrid	1D-PIC
$\epsilon_e \sim$???	$\epsilon_e \sim 0.0001$



Park, Caprioli & Spitkovsky 2015


Non-relativistic
Trans-relativistic
Relativistic
ϵ_e
PIC simulations of quasi-parallel shocks with Alfvenic Mach number ~10-20
$\epsilon_e \sim 0.1$
Sironi & Spitkovsky 2011
$\epsilon_e \sim 0.0001$
Park,Caprioli, Spitkovsky 2015
0.1
15
$\Gamma_s \beta_s$

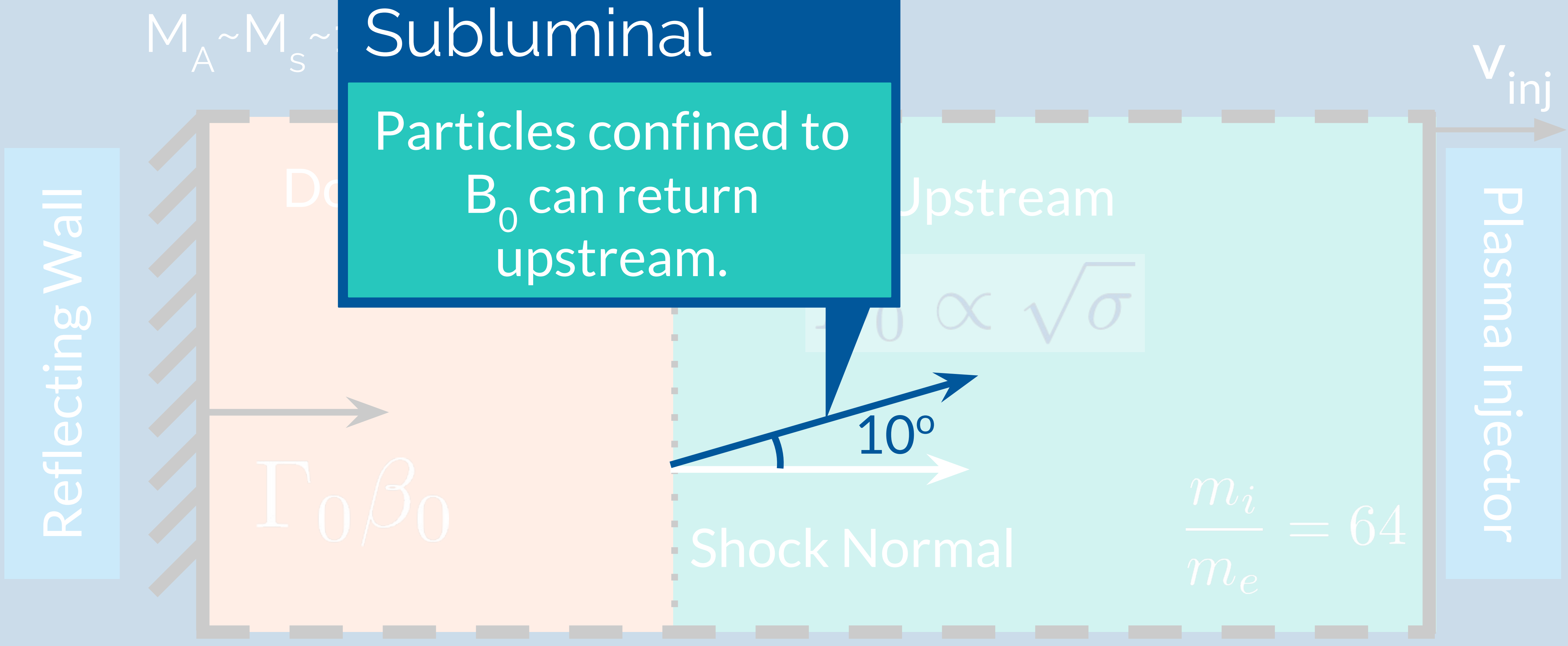
Simulation Set-up



Simulation Set-up

Subluminal

Particles confined to B_0 can return upstream.



Mildly-Relativistic quasi-parallel shocks

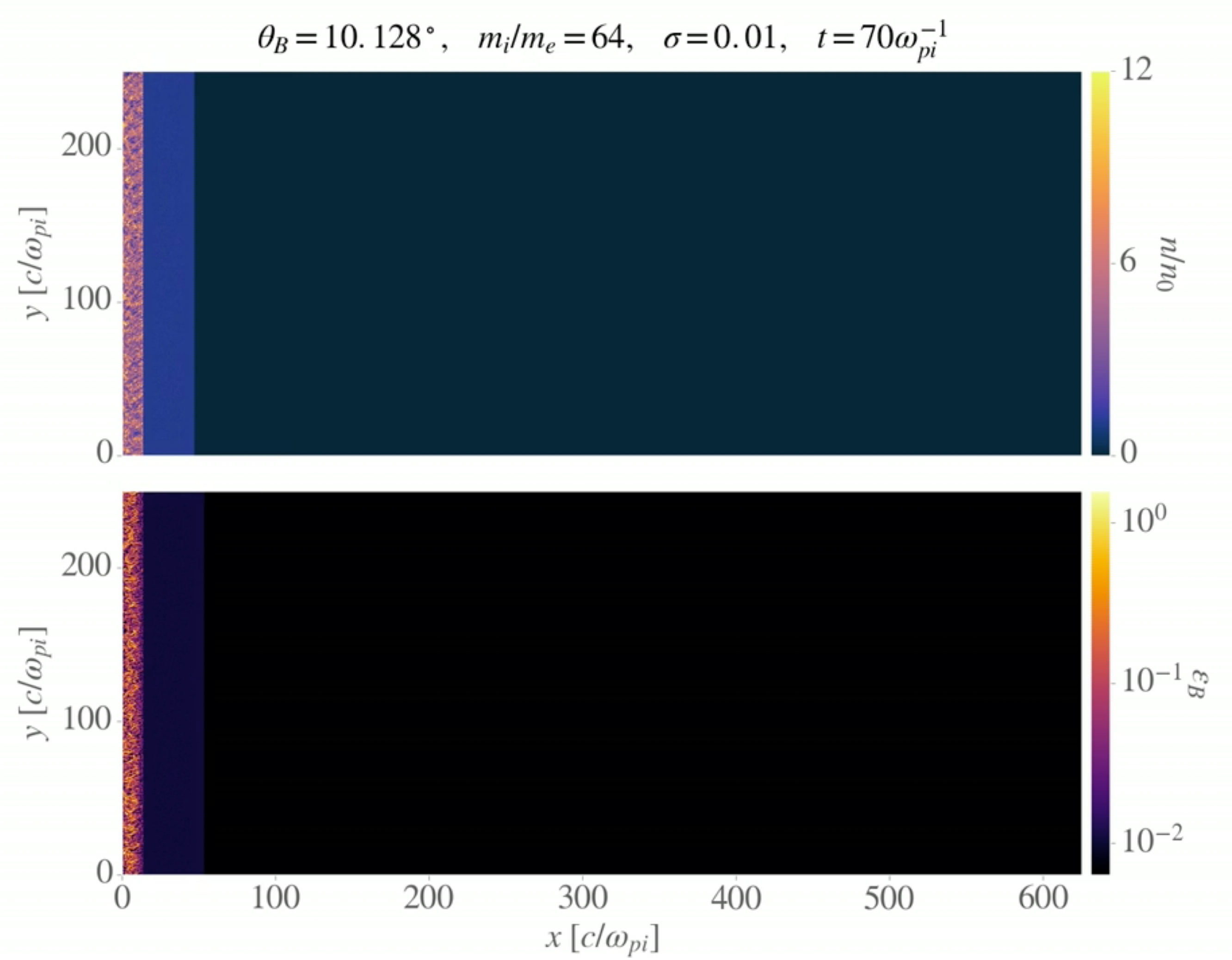
Simulation set-up

$$\gamma_0 = 1.5$$

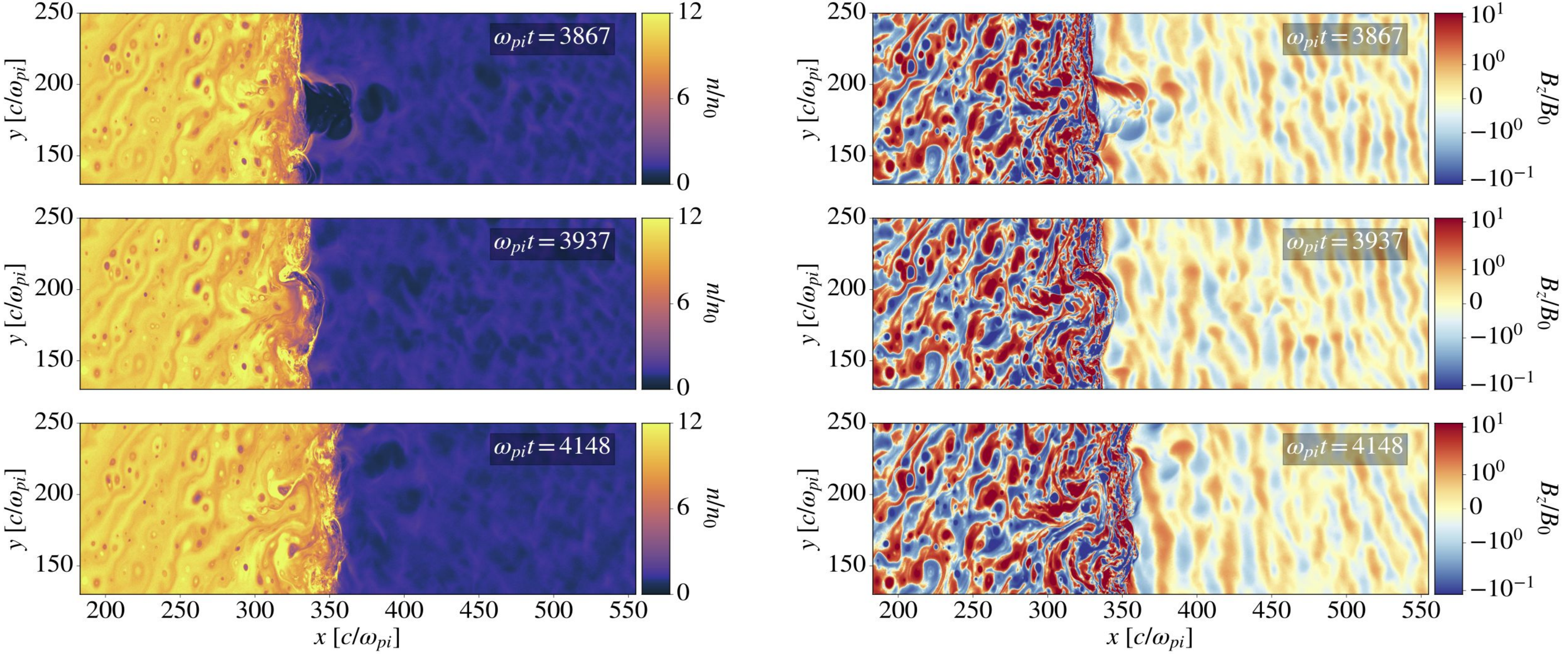
σ = 0.01

θ_B = 10º

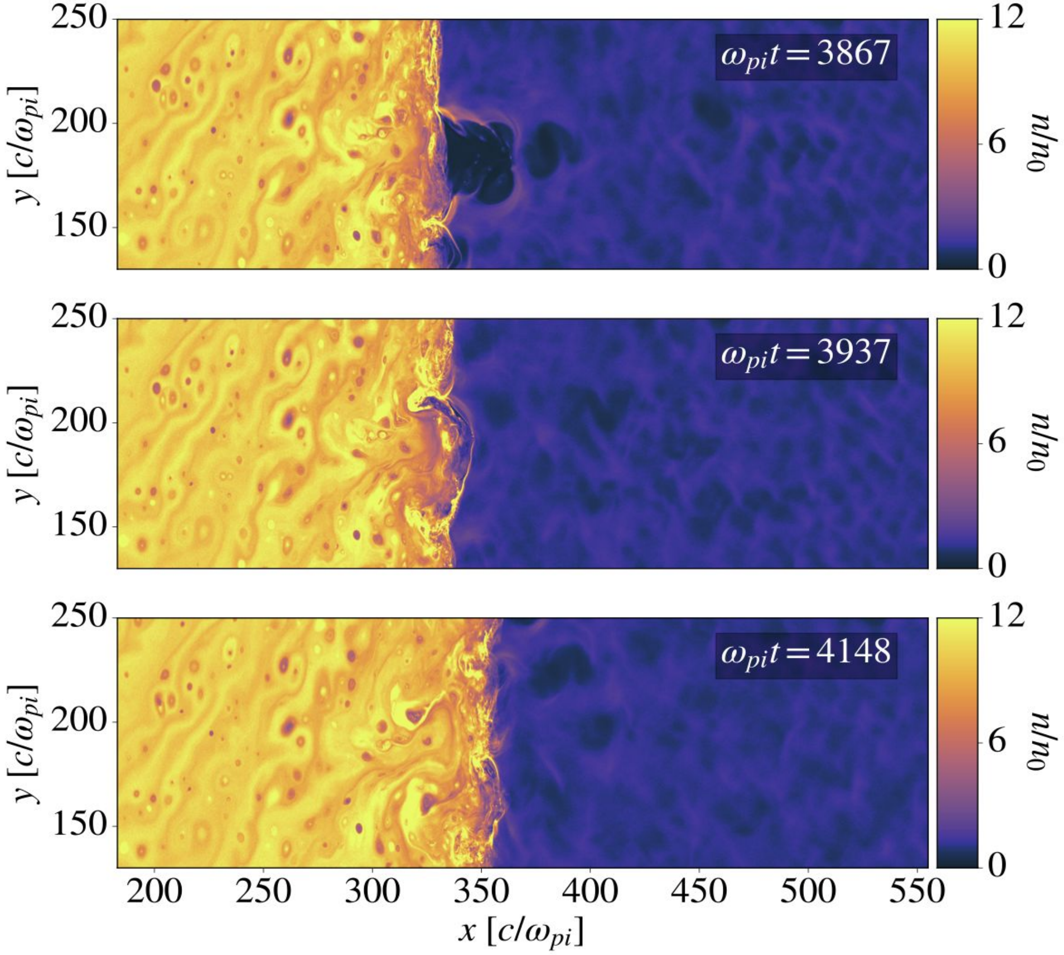
$$\beta_p = 1$$

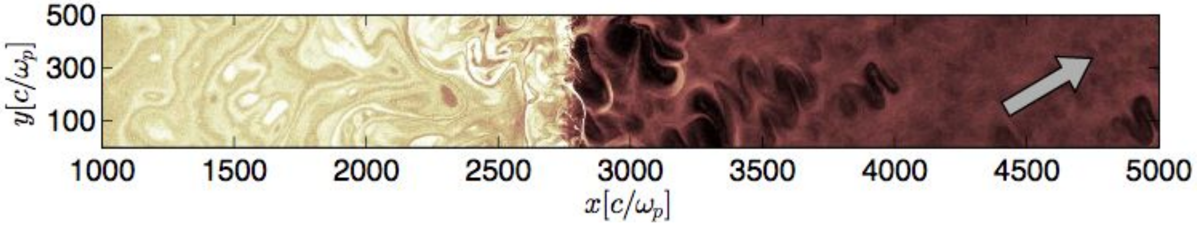


Mildly-Relativistic quasi-parallel shocks



Mildly-Relativistic quasi-parallel shocks





Caprioli & Spitkovsky 2014

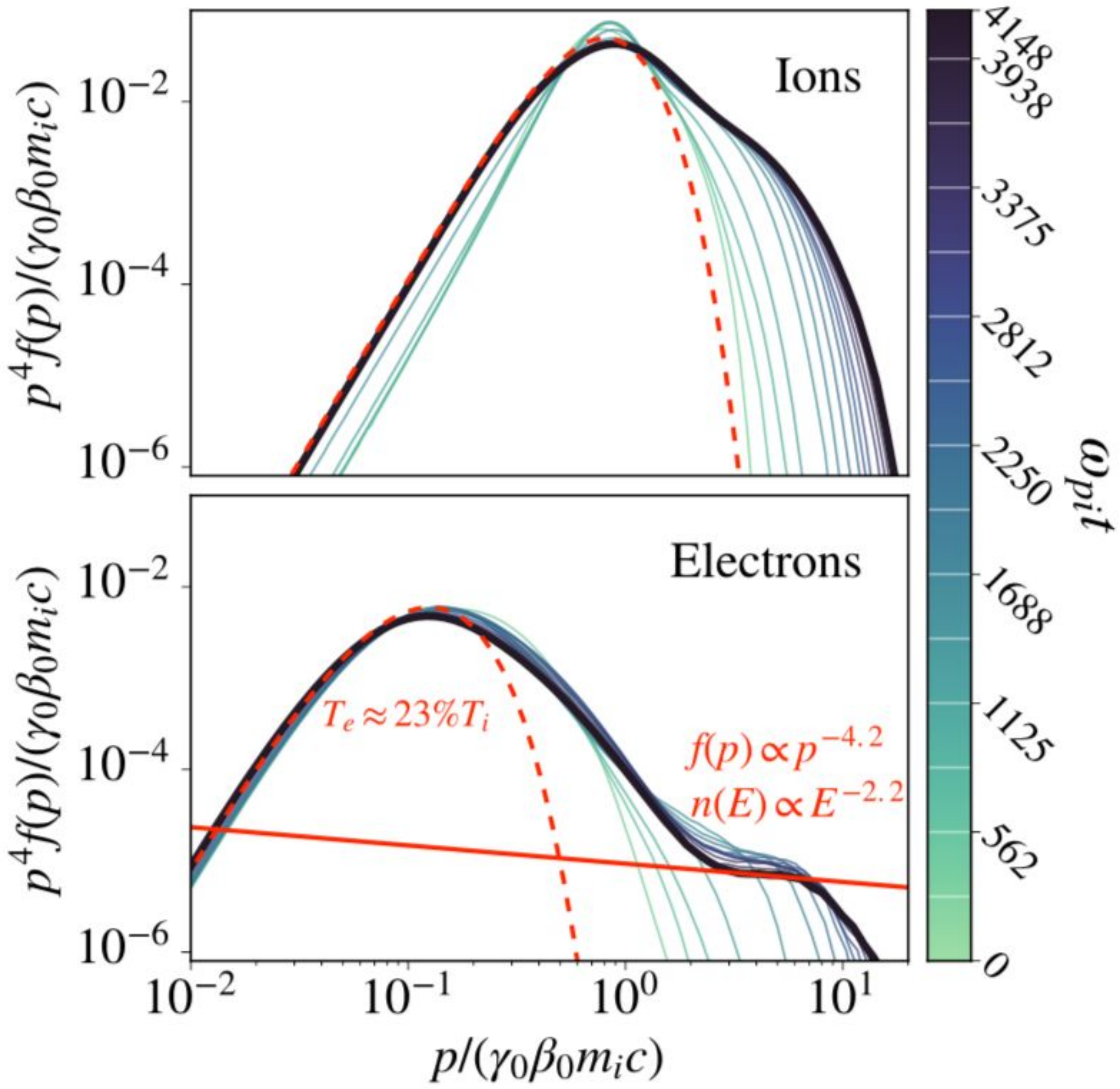
Fully kinetic simulations that capture the high-energy ion-driven turbulence discovered using Hybrid simulations.

Spectra:

Only a small fraction of the shock's energy is in non-thermal electrons.

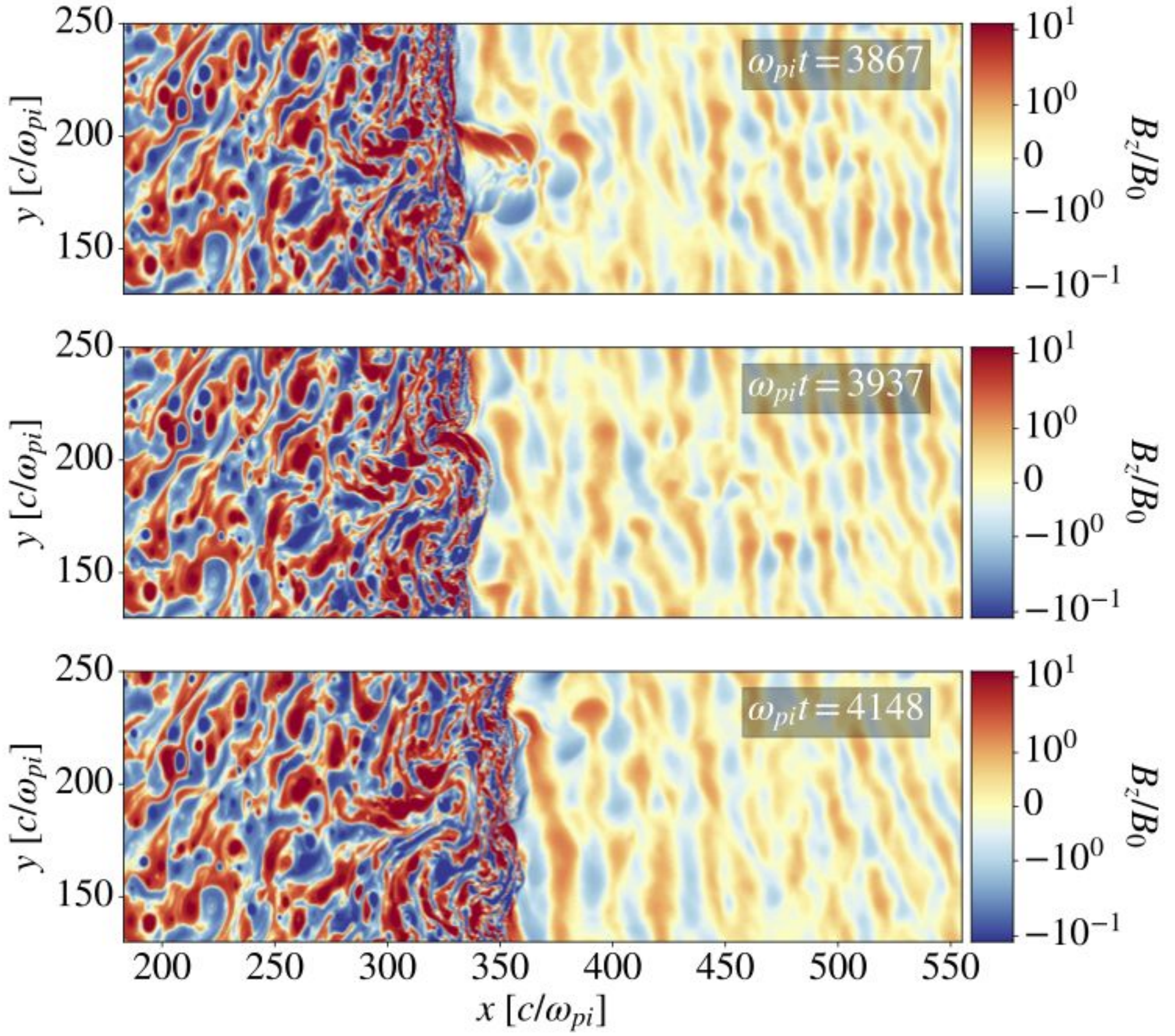
$\epsilon_p \sim 0.1$

$\epsilon_e \sim 10^{-3}$



Fields:

Non-resonant ion instability creates large scale transverse fields that are good at scattering particles back towards the shock.



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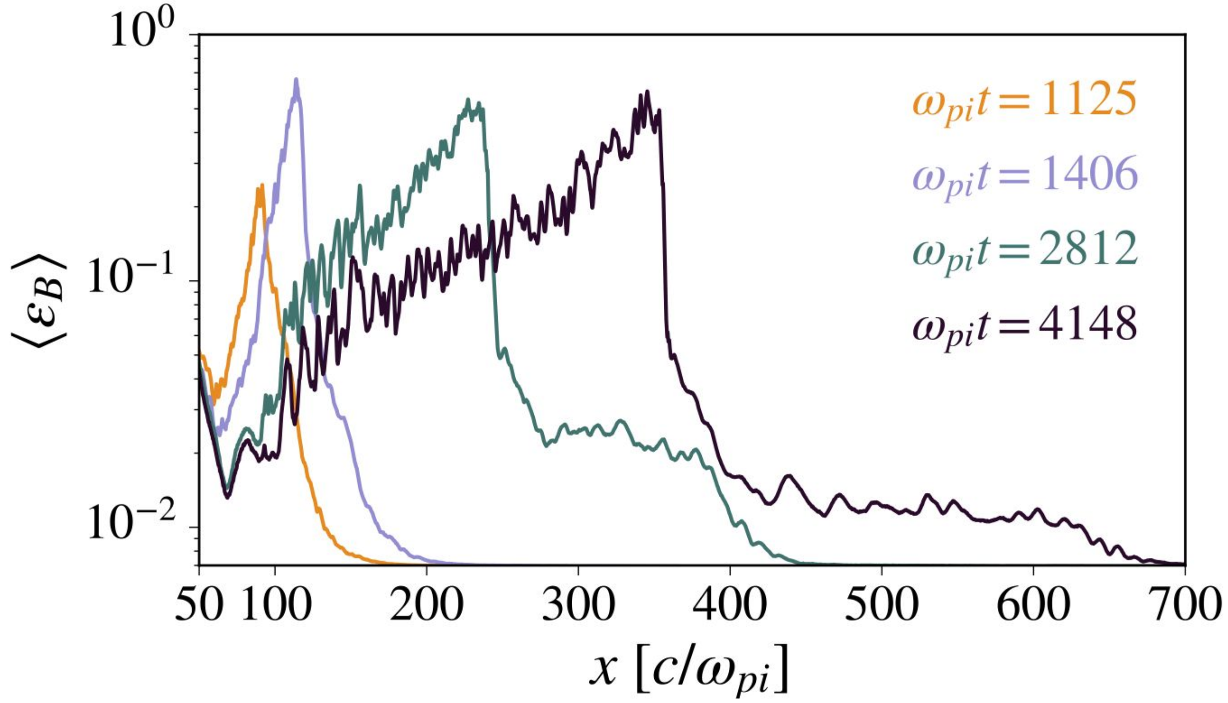
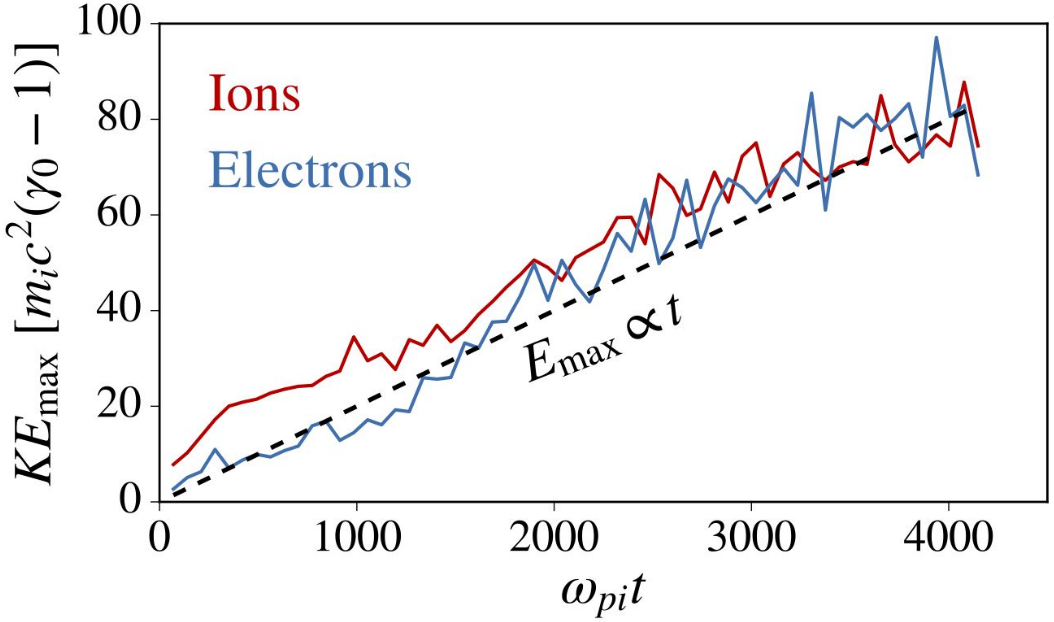
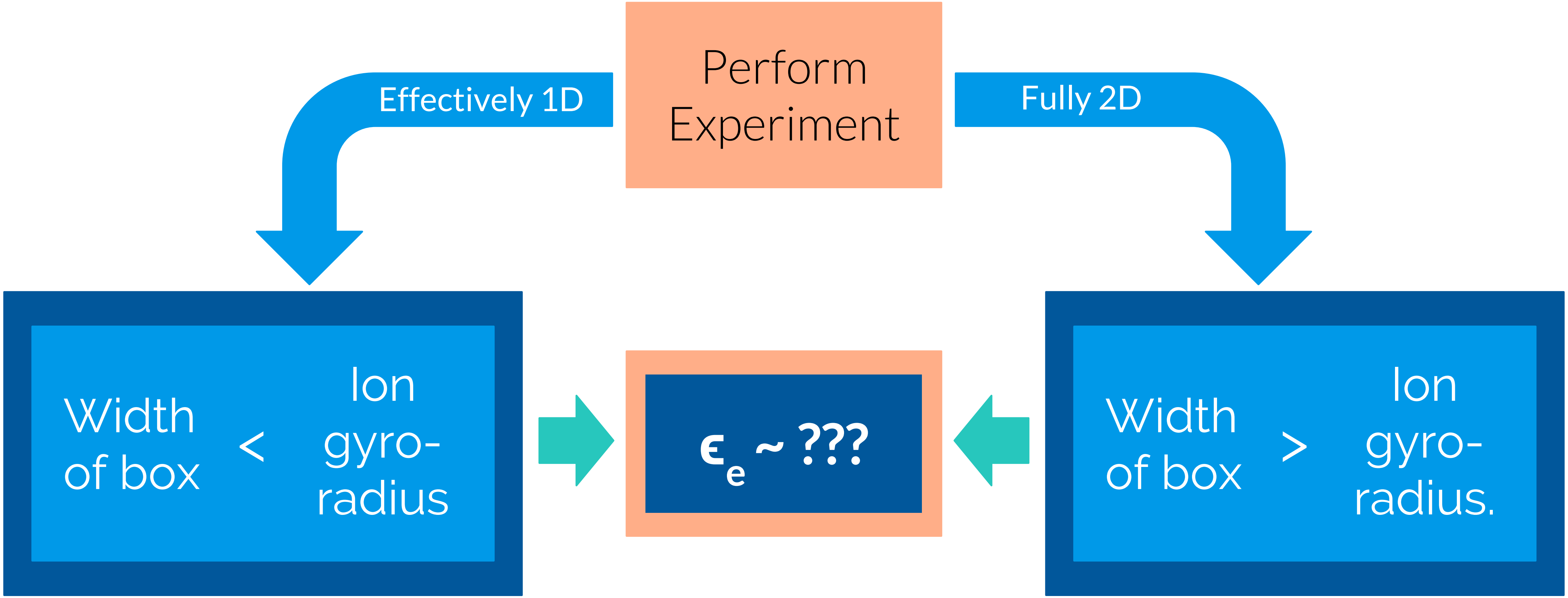


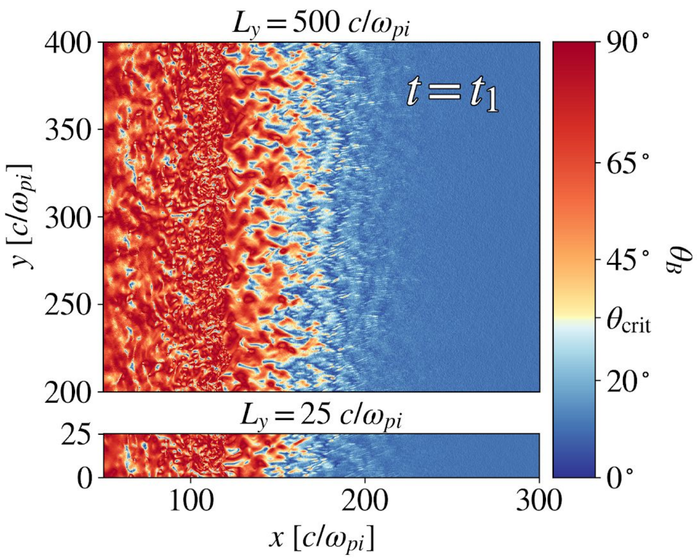


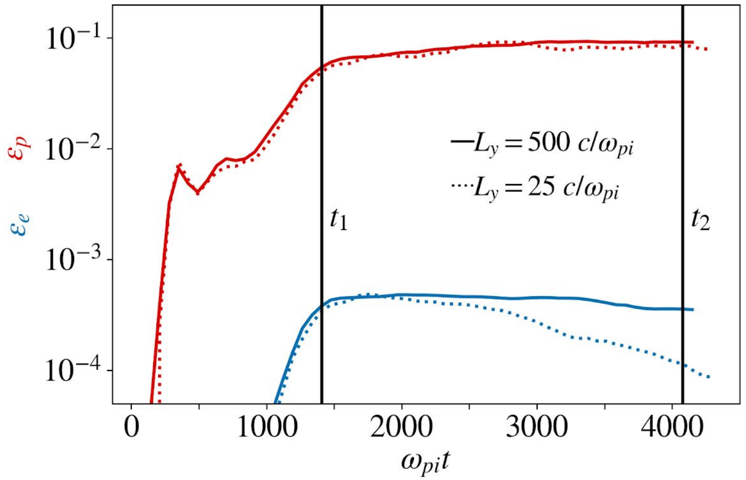
Do the filaments matter?

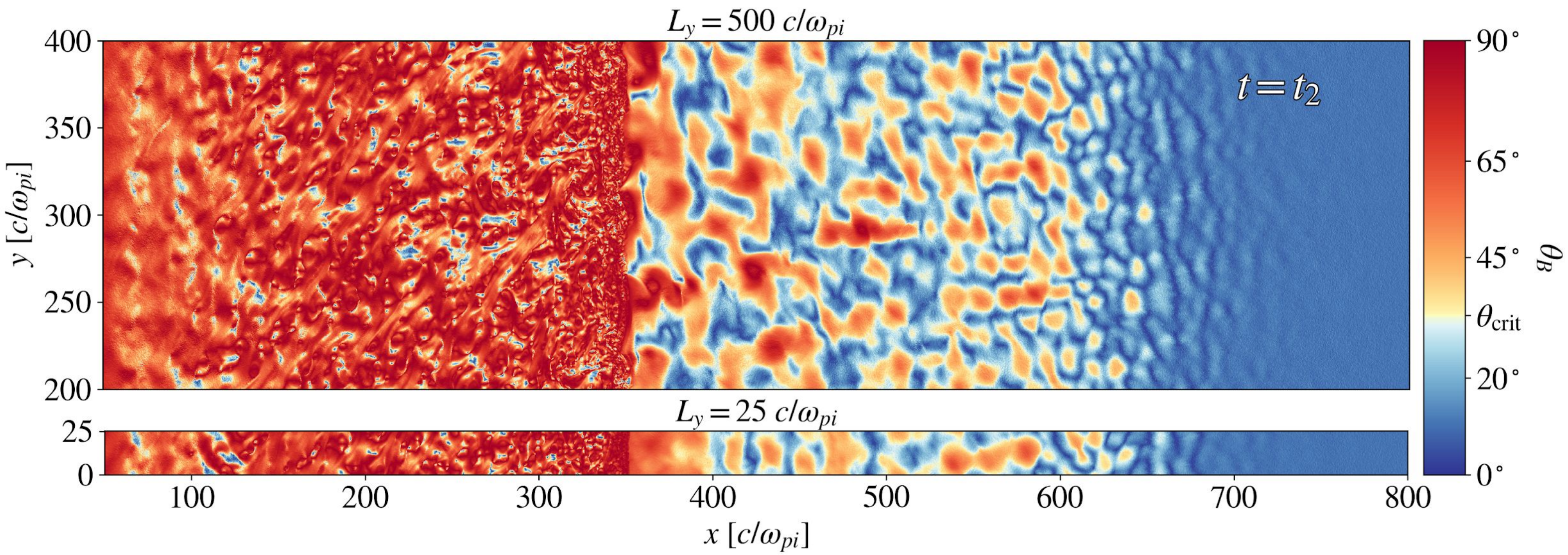


Filaments:

The filamentation creates regions of quasi-parallel and quasi-perp fields, making it easier to inject electrons.



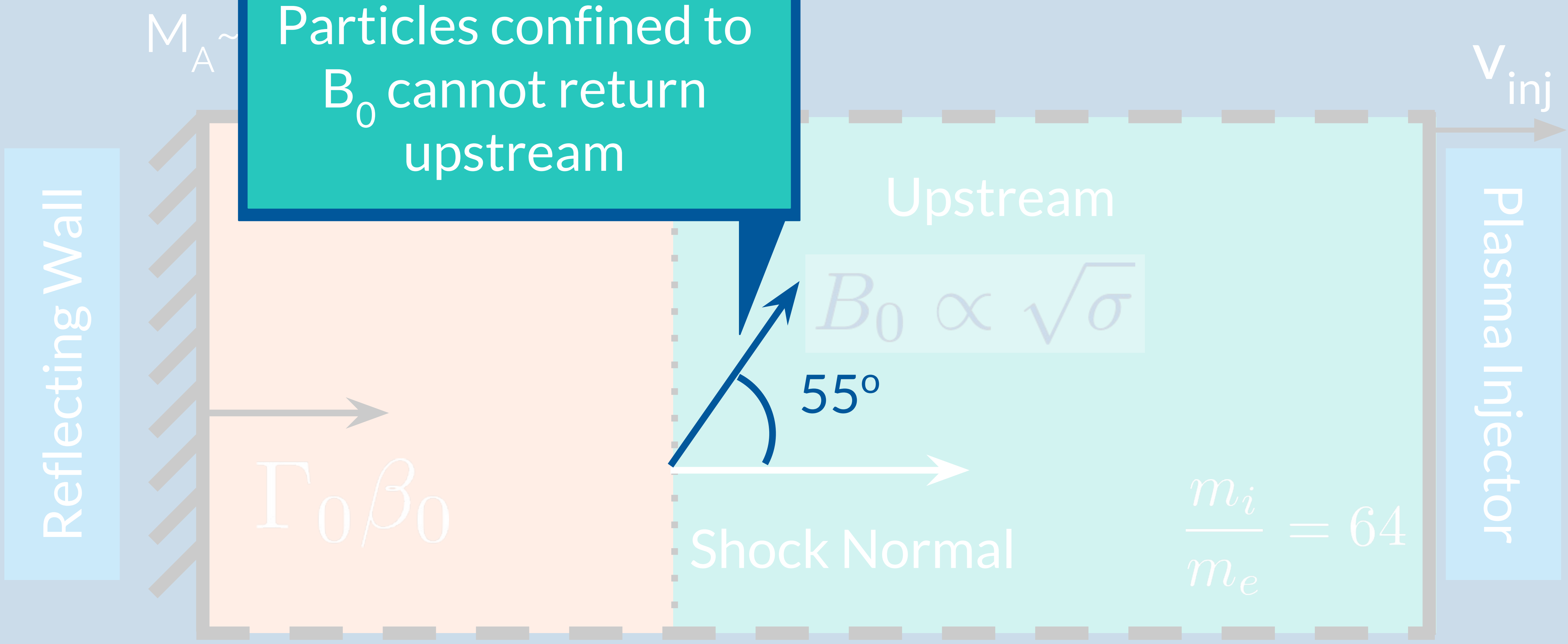




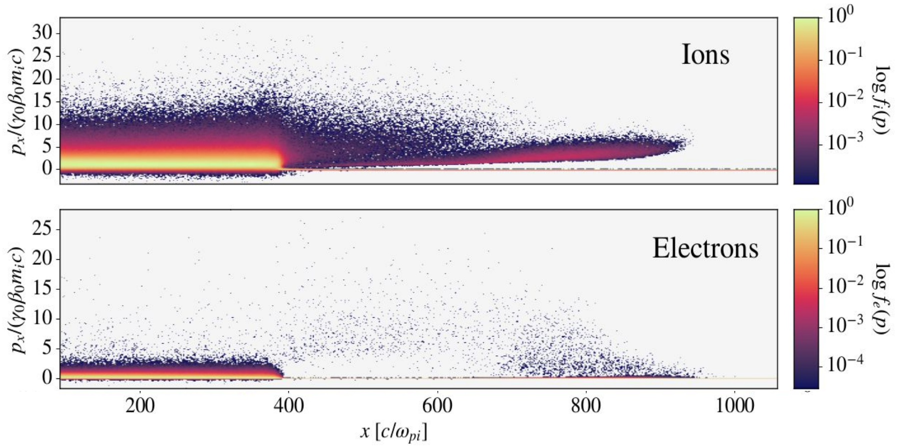
Superluminal

Particles confined to B_0 cannot return upstream

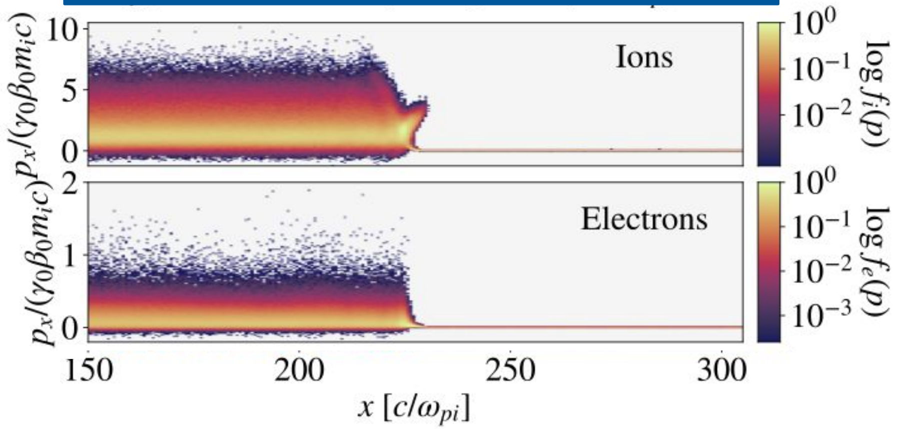
n Set-up

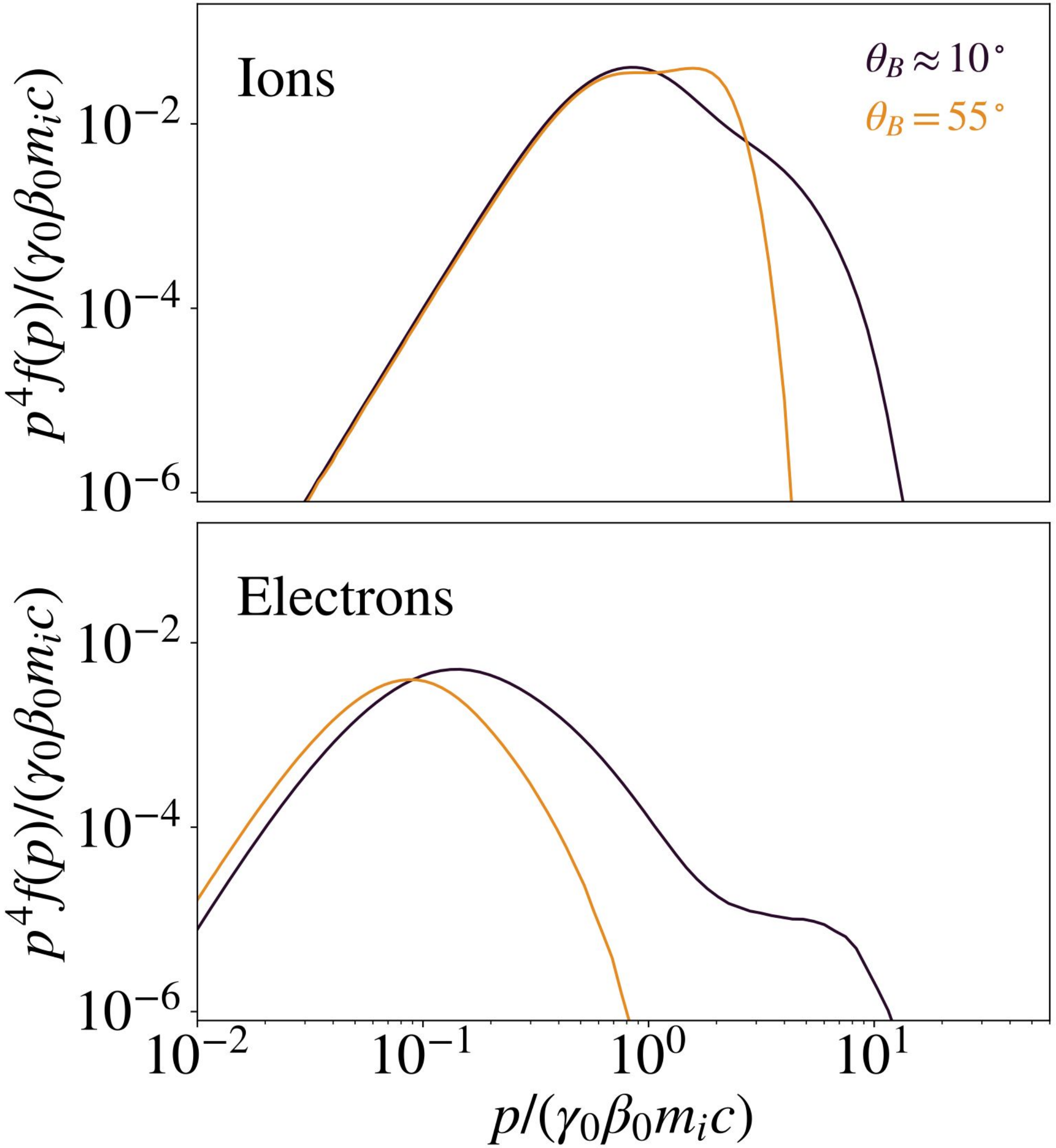


Subluminal

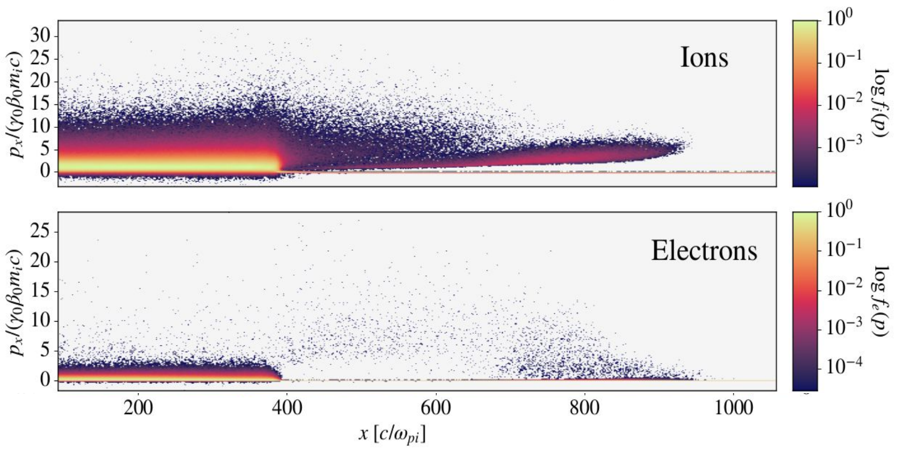


Superluminal

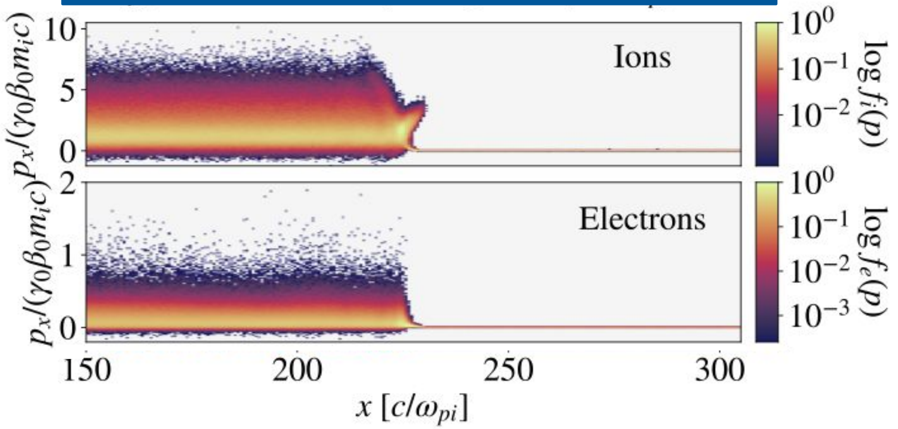




Subluminal



Superluminal



Differences in superluminal and subluminal orientation similar to what was found for relativistic shocks.

But mildly relativistic shocks more likely to be subluminal

How does $\boldsymbol{\epsilon}_e$ change with Lorentz factor of shock?

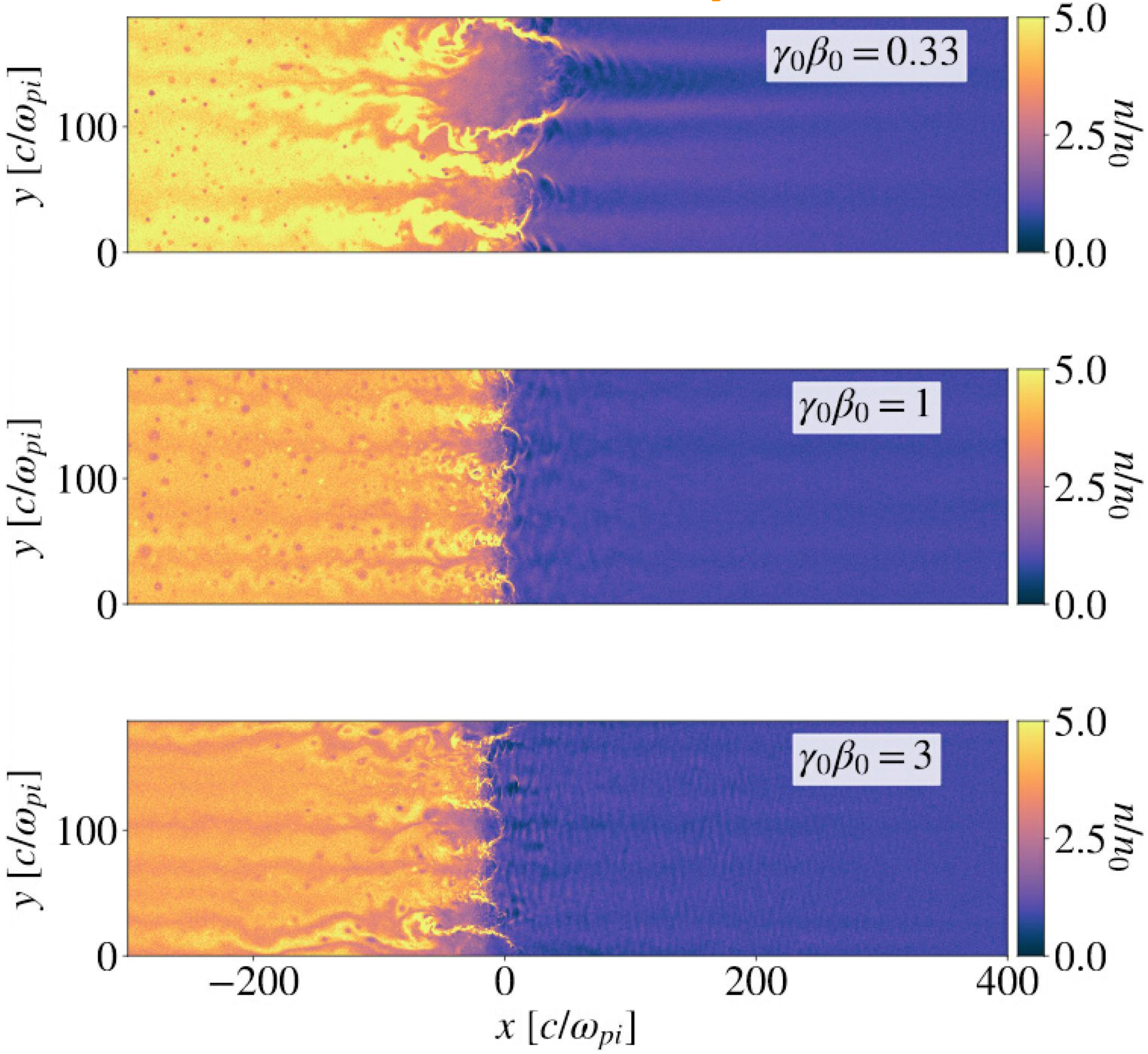
Simulation set-up

$\boldsymbol{\sigma} = 0.01$; $\theta_B = 0$

$$\gamma_0 \beta_0 = 0.33,\ 1,\ 3$$

Mildly-Relativistic parallel shocks

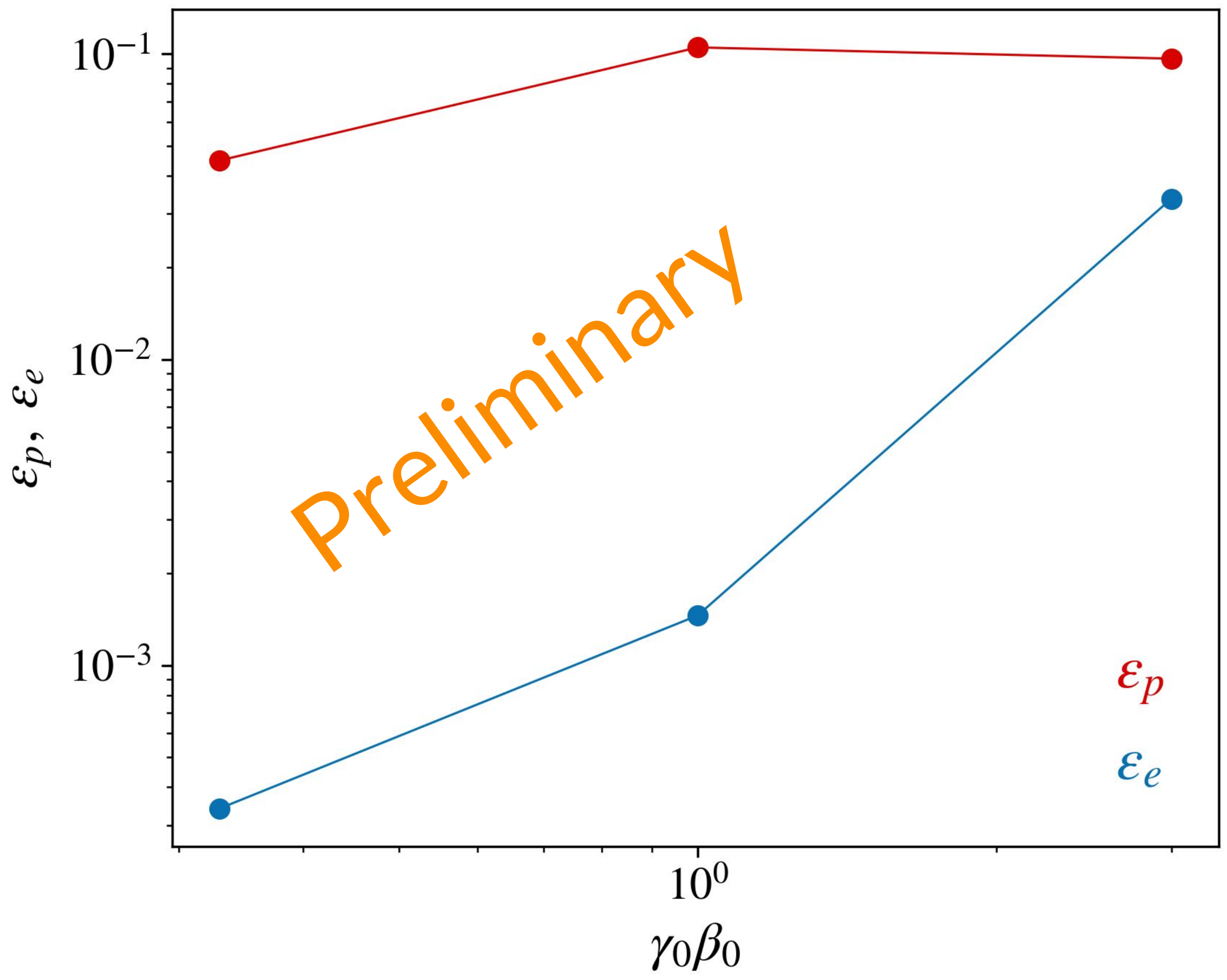
Preliminary



All velocities show the filamentation instability.

Mildly-Relativistic parallel shocks

We see evidence for a large increase in ϵ_e as v->c.



Caveat: ϵ_e likely depends on M_A, T, θ_B... Shock Speed is not only important parameter

Conclusions:

- We have examined particle acceleration in magnetized mildly relativistic shocks fully kinetic PIC simulations.
  - Quasi-parallel shocks are efficient ion and inefficient electron accelerators. Quasi-perp, superluminal, shocks do not produce power-law distributions.
- We used unprecedentedly large boxes to capture non-resonant ion driven turbulence in quasi-parallel shocks.
  - Large scale transverse upstream fields scatter particles back towards the shock, and filaments at the shock front allow electrons to return upstream.
- Preliminary simulations of magnetized quasi-parallel shocks show that ϵ_e increases from ~10^{-3} to ~a few x 10^{-2} as the shock velocity goes from 0.33c to 0.95c, while ϵ_p remains ~constant.
  - A varying ϵ_e with velocity may be directly tested through modeling observations of objects that pass through the mildly relativistic regime -- e.g. GRB afterglows at late times.